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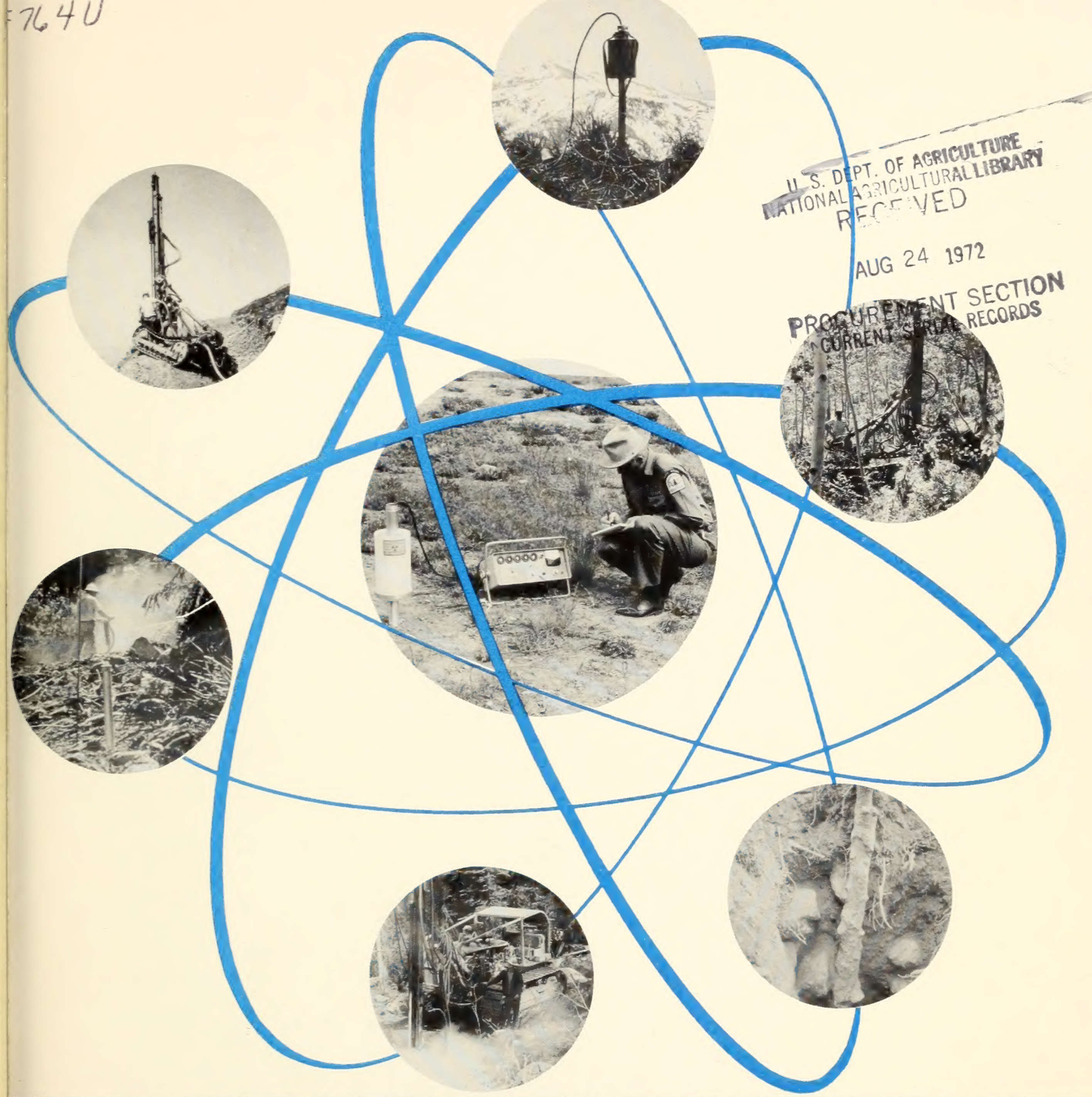

EFFECTS OF AIR GAPS AND SATURATED VOIDS ON ACCURACY OF NEUTRON MOISTURE MEASUREMENTS

Bland Z. Richardson and Edward R. Burroughs, Jr.

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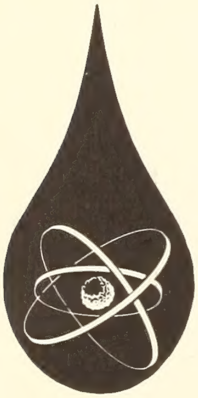

BLAND Z. RICHARDSON is a Research Forester stationed at the Forestry Sciences Laboratory of the Intermountain Forest and Range Experiment Station, Logan, Utah. After completing engineering training at Yale University in 1944, Richardson was commissioned in the United States Air Force where he served as an Aircraft Engineering Officer until his retirement from active duty in 1952. From 1952 until 1959, Richardson operated his own forest management business in the Southern Pine region. Richardson attended the University of Montana from 1960 to 1963 where he received a B.S. degree in forestry. In 1964 he joined the Intermountain Forest and Range Experiment Station and was assigned to research work in the field of watershed management. Since then he has been involved in a variety of research activities in that field including studies to determine the effects of multiple logging roads on soil moisture regime; the hydrologic and pedologic effects of grazing on rangelands; the infiltration and erosional behavior of contour trenches on high elevation mountain watersheds; and the effects of voids and measurement techniques on the accuracy of neutron soil moisture determination. In 1966 Richardson was awarded a Certificate of Merit by the USDA Forest Service. Other schools attended include the Air University; Arlington State College; Texas Christian University; and Utah State University.

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EFFECTS OF AIR GAPS AND SATURATED VOIDS ON ACCURACY OF NEUTRON MOISTURE MEASUREMENTS

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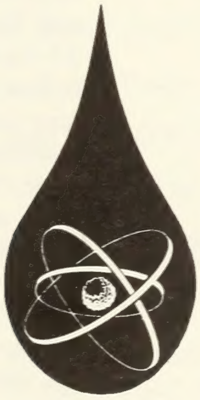
Bland Z. Richardson and Edward R. Burroughs, Jr.



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ABSTRACT

The effects of voids on the accuracy of neutron soil moisture measurements in coarse and fine sand were investigated utilizing two 25-cubic-foot plastic tanks. Test voids 3 inches and 6 inches in diameter and 10 inches long were cut from aluminum tubing and fastened to the neutron access tube in each tank. Voids in the control tank were filled with sand; those in the test tank were left empty. The amount of water which was added or subtracted was measured by weighing each tank. The difference in neutron measurements between the two tanks with the water at a given level measures the effects of the voids.

A maximum error of +55 percent moisture by volume was caused by the large void in coarse sand with the void saturated; with the void drained, the error was -12.3 percent moisture. Errors in fine sand were slightly less than those in coarse sand; and errors due to the small void were about one-third the magnitude of errors due to the large void. Graphs were developed for use in estimating the size of voids adjacent to access tubes and in calculating the probable magnitude of measurement errors due to these voids when using field data.

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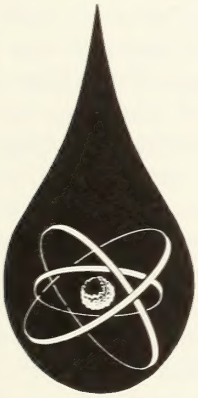

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INTRODUCTION

The neutron method of measuring soil moisture is widely accepted by hydrologists and soil scientists because the method can be fast, easily performed, and accurate. Accuracy is due primarily to the large volume of soil sampled, nevertheless it is essential that the sample be truly representative of the soil within the measured zone. If a soil void is adjacent to an access tube an error in measurement will result. The magnitude of the error is a function of the size and shape of the void as well as the volume of water within the void. Soil voids, due primarily to poor installation techniques, cause the greatest errors in neutron moisture measurements.

Many installation techniques will give satisfactory access tube installation in rock-free soils. However, in rocky wildland soils, special access tube installation procedures must be used to prevent voids between the soil and the tube (Richardson 1966). Unfortunately, literature that pertains specifically to the use of neutron meters in wildland soils is scarce; furthermore, literature dealing with the effect of voids on neutron moisture measurements is almost non-existent. Koshi (1966) tested various methods for drilling access holes in rocky soils and concluded that the holes must be drilled oversized to compensate for irregularities in the dimensions of the drilled hole. These holes were then backfilled with screened soil to remove any air gaps in the soil next to the access tube. Koshi also tested the effect of 1/8 inch to 3/8 inch air gaps next to access tubes installed in loamy soil and concluded that there was no effect. Troxler (1963) has suggested that 0.15 inch is the maximum air gap that can be tolerated without error.

If the soil profile never becomes saturated, then the effect of small air gaps is negligible. If the soil moisture regime is such that the ground water level fluctuates seasonally, then a small air gap next to the access tube introduces a small error in the summer when the soil is relatively dry. However, this fluctuation causes an unknown but much larger error when the water table rises and saturates a soil void (Burroughs 1967). In a study of soil moisture on wildland soils, Burroughs concluded that backfilling cannot be relied upon completely to fill all voids left by the installation process. Another conclusion was that the first indication of a serious void problem occurs when the void becomes saturated. Abnormally low neutron counts cannot be taken as prima facie evidence of a large air filled void. Koshi (1966) showed that a large rock next to the access tube may also cause a drop in count rate.

This paper describes a laboratory study of the error caused by voids adjacent to access tubes in a uniform porous medium when the soil moisture content changes from a fully saturated to a drained condition. The objectives are to define quantitatively the neutron errors so that scientists may have guides to detect the presence of voids and estimate the magnitude of the error associated with them.

METHODS AND PROCEDURES

The controlled conditions implicit in a laboratory study of the effects of voids on accuracy of neutron soil moisture measurements require that:

1. The volume of the porous medium be large enough to model a natural soil of infinite lateral extent.
2. The porous medium have a constant density throughout.
3. There be a reliable method for measuring the depth to the water table within the porous medium.
4. There be a reliable method for measuring the amount of water stored within the porous medium.

The effects of voids were measured within two 25-cubic foot plastic tanks; one tank served as a control, and the other tank was used for tests (fig. 1). Each tank had walls 0.50 inch thick and was 67-1/2 inches deep and 29 inches in diameter (inside dimensions). These dimensions were selected because a study by Marston (1965) showed that a radius of approximately 14 inches in drained soil is sufficient to contain the sphere of influence for a neutron soil moisture meter for readings taken at depths greater than 12 inches. In our study, a tank radius of 14-1/2 inches was considered to represent a volume of infinite lateral extent. A concave steel bottom equipped with a strainer and drain was fastened to each tank. A steel lid with a 2-inch hole to accommodate an aluminum soil moisture access tube was placed over the tank to prevent evaporation of water from the interior. Eight steel tension rods were spaced equally around the tank to clamp the top and bottom securely. A manometer made of plastic

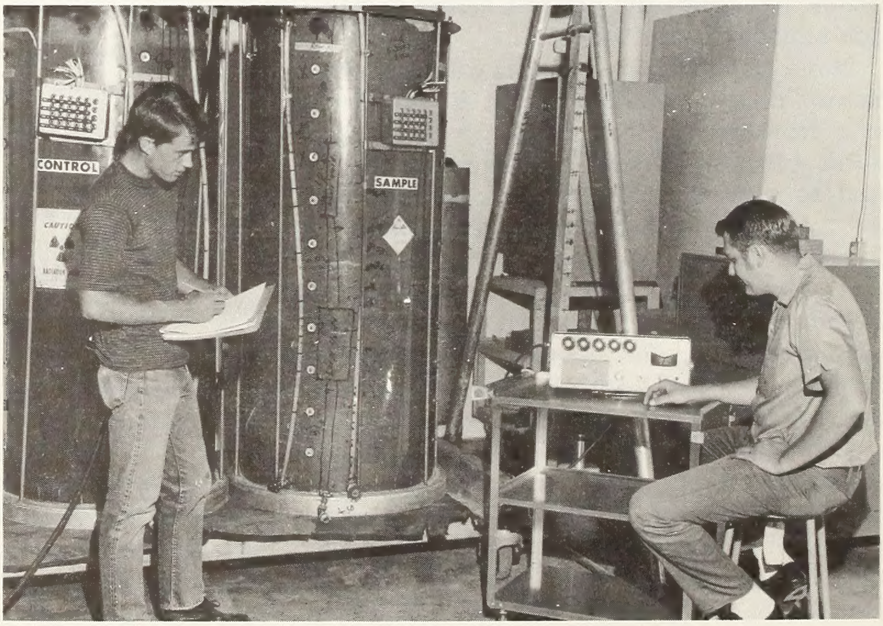

Figure 1. — Measurement of the effects of voids were made within two 25-cubic-foot plastic tanks. The sample tank contained built-in "voids" while the control tank had none.

pipe was threaded into the wall of the tank 1 inch above the bottom to indicate the level of the free water surface within the tank.

Forty holes 1-1/8 inches in diameter, and arranged in four vertical rows of 10 holes each, were drilled through the walls of each tank to check bulk density of the porous medium. These vertical rows were spaced equally around the tank and the holes within each row were spaced equally from top to bottom. The holes were sealed by expanding plugs made from black rubber stoppers having washers on each face and pierced by bolts. The plugs were compressed and expanded when the bolts were tightened.

The dimensions for the test voids were selected after an examination of field data from six access tubes. These tubes had been installed 6 feet deep and showed an extremely large seasonal fluctuation in soil moisture. Three of the tubes yielded neutron counts that seemed "reasonable," i.e., percent moisture by volume did not exceed soil pore space when soil was saturated. The remaining three tubes yielded questionable data, i.e., data indicating that the percent moisture by volume exceeded the pore space of the soil.

Castings were made of the access holes. Before this could be done, the rubber stoppers sealing the bottoms of the access tubes had to be removed. Cement was poured into the tubes and 3/8-inch reinforcing rods were used to work the mortar gently out the bottom of the tubes. As the cement flowed out into each of the access holes, the access tube was raised slowly and the reinforcing rod was left in the hole. When the access hole was filled completely with cement, the access tube was removed; and the cement was allowed to harden for 2 weeks. Then the castings were excavated (fig. 2) and measured. The three access holes yielding questionable data had voids, as determined by the castings, that ranged in size from 3 to 6 inches in diameter and up to 10 inches long.

The small and large test voids were made from 10-inch lengths of 3- and 6-inch-diameter aluminum irrigation pipe having wall thicknesses of 0.010-inch. These test voids represented two symmetrical voids with 1/2- and 2-inch annular space around the access tube (fig. 3).

A heavy pipe frame was erected in the laboratory to support an "I" beam which acted as a track for a rolling carriage that carried a hydraulic cylinder. Four lifting bars were attached to the top of each tank. When the hydraulic cylinder was attached to the lifting bars a small hydraulic hand pump was used to actuate the cylinder and lift the tank for weighing.

A coarse sand and a fine sand were used as the porous mediums for the study. Of the

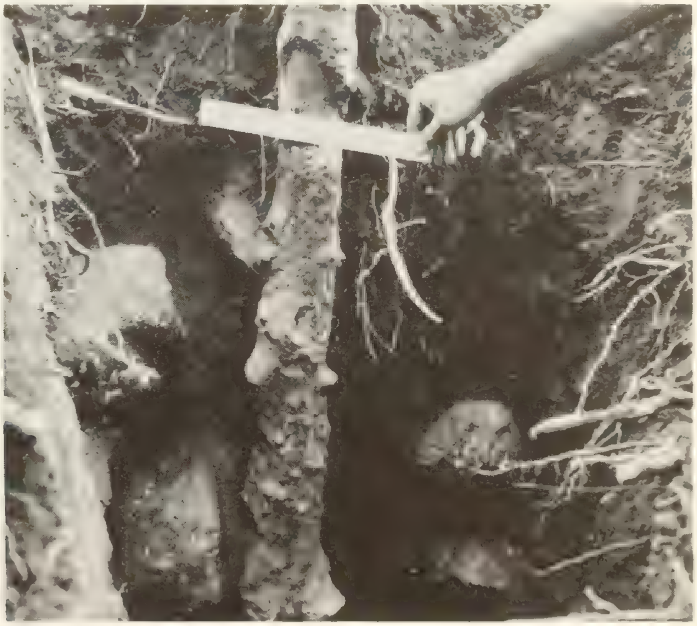

Figure 2. — Access tube castings were excavated for shipment to laboratory. Some of the six castings showed voids up to 6 inches in diameter and 10 inches long.

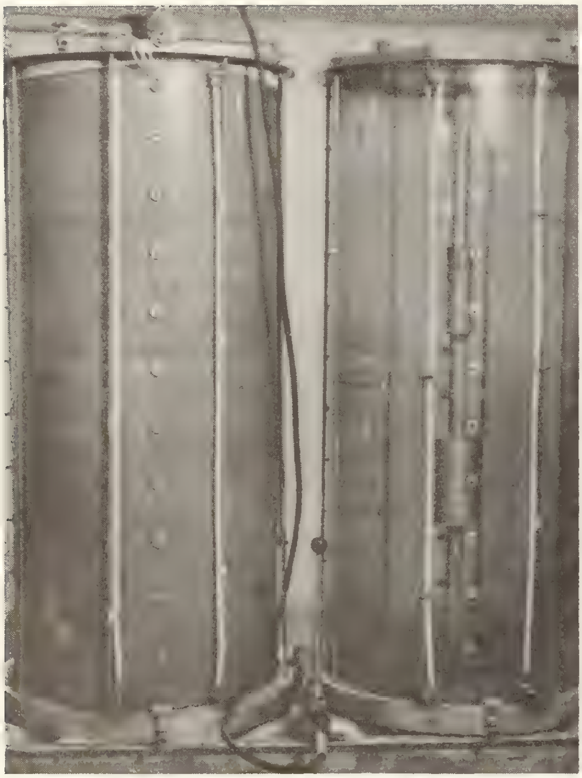

Figure 3. — The left tank has been filled with sand. The small and large "voids" can be seen in the right tank. Manometers are mounted on the front of each tank. Plugs in the sides of tanks provide access for obtaining density and moisture samples.

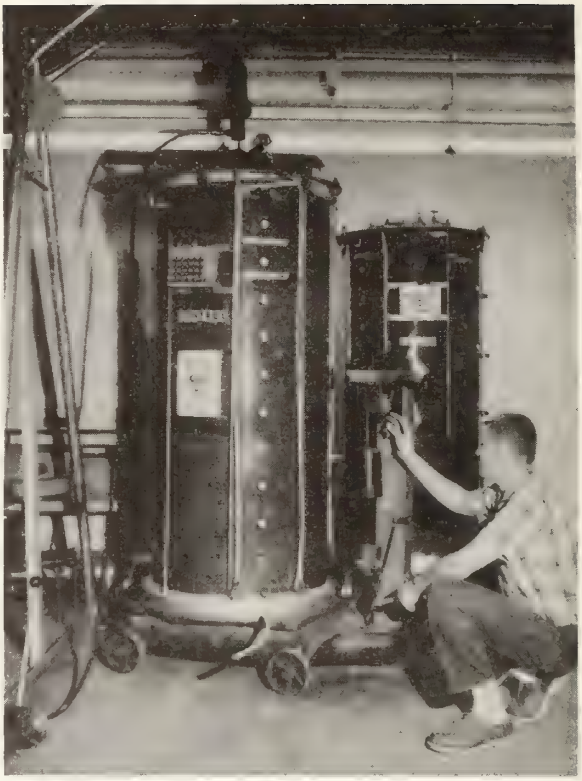

Figure 4. — An "I" beam, supported by steel "A" frames, serves as a track for a hoist used to lift tanks for weighing. Each tank was weighed while dry, after each change in water level, and at saturation.

coarse sand, 99 percent passed a #16 Tyler screen (1.00 mm.) and not more than 1.47 percent passed a #32 Tyler screen (0.500 mm.). Of the fine sand, 99 percent passed a #32 Tyler screen and only 18.73 percent passed a #60 Tyler screen (0.250 mm.) Before the tanks were filled with sand, the access tubes were centered in the tanks. Coarse sand was released from an overhead hopper through a hose in such a way that the particles had a constant fall distance and constant initial velocity to assure a constant bulk density.[1] When the level of sand in the tank reached 18 inches above the bottom, the large 6-inch-diameter void tube was slipped down over the access tube and allowed to rest on the sand. Pouring was resumed until there were 13-1/2 inches of sand over the top of the large void. Then the small 3-inch diameter void was slipped onto the access tube and filling with sand continued until there were 14 inches of sand over the small void and the sand was 2 inches from the top of the tank. This procedure was used to fill both tanks; however, in the control tank the test voids were filled with sand before the top of the void was attached. The only difference between the two tanks was that the test (sample) tank had empty voids and the control tank had voids filled with sand.

The tanks were positioned under the pipe frame and weighed (fig. 4) to determine the dry weight of sand in each tank. A hose was attached to the drain on the bottom of each tank and the tank was slowly filled with water from the bottom. It was then drained and refilled to remove all air from the sand. Each tank was reweighed when filled so that the total weight of water in the sand could be calculated.

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[1] *Unpublished data in files of the Forestry Sciences Laboratory, Logan, Utah.*

A Troxler neutron soil moisture meter was used to measure the moisture content at predetermined depths in each tank under conditions of changing water levels. Thirteen water levels, measured in inches from the surface of the sand, were selected for this study (fig. 5). A one-minute counting period (Merriam 1962) was used at each of these 13 water levels. The center of measurement for the probe was assumed to be the center of the detector tube. After a set of 13 one-minute counts, the water level was lowered or raised to the next water level and the neutron measurements were repeated at all 13 water levels. Each set of readings was bounded by a set of 5 one-minute standard counts. The water which drained from the tank when the water level was lowered to the next stage was collected, measured, and compared with the weight of the tank before and after the change in water level. When the neutron measurements were completed on one tank (i.e., from a saturated to a drained condition), the process was repeated on the second tank. After all neutron measurements were completed, a series of bulk density samples were taken; the tanks were emptied and refilled with the fine sand.

Three sets of bulk density measurements were made in each of the two tanks: (1) small (142 cc.) gravimetric samples were taken through the side of the tank; (2) measurements were made with a Troxler depth-density gage; and (3) large (6,300 cc.) gravimetric samples were taken adjacent to each void when the tanks were emptied.

The small sampler consisted of a length of stainless steel conduit having an inside diameter of 1.05 inches; it was machined on the outside to a 1.12-inch diameter and had a flange acting as a stop to allow the sampler to penetrate 10 inches into the sand. After the tank had drained for 24 hours, a plug was removed from a sampling hole, and the small sampler was inserted. The 142-cc. sample was withdrawn, emptied into a can, weighed, and placed in an oven for drying and reweighing. As soon as the sampler was emptied, the sand was replaced by a sample drawn from a container of damp sand filled to the same bulk density from the overhead hopper. The replacement was inserted into the tank and held in place by a wooden plunger while the sampler was withdrawn and the rubber plug was replaced.

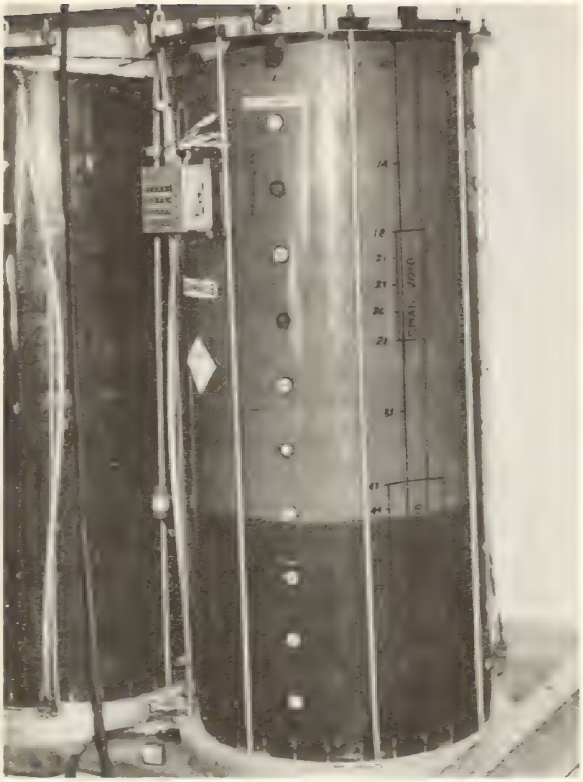

Figure 5. — Darker portion of tank on right is caused by rising water. Drawing on side of tank shows size and location of the small void and the large void within the tank. Numbers are in inches, measured from the surface of the medium.

The second set of samples was taken by lowering the Troxler depth-density gage into the access tube and measuring at each of the 13 levels.

The large gravimetric samples were taken at four levels in each tank. The first sample was taken after 4 inches of sand had been removed from the tank. The sampler was forced into the sand, the surrounding sand was removed, a piece of sheet metal was inserted under the sample, and the sample was removed from the tank; the sample was weighed, dried, and then reweighed. Another sample was taken between the small void and the wall of the tank; the center of the sample was on a level with the center of the void. A third sample was taken on a level corresponding to the center of the tank, and a fourth sample was taken opposite the large void.

RESULTS

Table 1 shows the bulk density of the two types of porous media as determined by the four methods: (1) large gravimetric sample; (2) small gravimetric samples; (3) the Troxler density probe; and (4) the ratio of the tank weight with dry sand to the volume of the tank occupied by the porous medium. This table shows that there is negligible difference in bulk density between the two tanks.

Most calibration curves show a linear relationship between neutron counts and percent moisture from zero to about 45 percent. A linear extrapolation of the calibration curve beyond 45 percent is not accurate because there is a curvilinear relationship between neutron counts and percent moisture beyond this point. For this study the factory furnished the authors with a calibrated curve used to convert neutron measurements to percent moisture by volume (fig. 6). Data from the control tank and the sample tank for a given water level were plotted on a master graph with depth of measurement on the ordinate and moisture content on the abscissa. An examination of the master graphs for each water level showed that the voids were far enough apart on the access tube to prevent an overlap in effects. Therefore, each master graph was redrawn as two graphs: one for data from the two tanks for depths of measurement which bracketed the small void; and another graph for data that bracketed the large void. Data points were connected to form two smooth curves which represent the soil moisture content at any depth in both the control tank and the sample tank when the water level was at a given depth. The effect of the void

Table 1. — A comparison of bulk density (in lb./ft.^{3}) in each tank for coarse and find sand as determined by four methods

	Small sample	Large sample	Troxler density probe	Tank wt./vol.
		COARSE SAND		
Control tank	98.9	99.8	101.5	99.9
Sample tank	99.2	99.6	100.2	99.9
		FINE SAND		
Control tank	101.6	100.9	(1)	102.4
Sample tank	100.9	101.3	(1)	101.7

[1] *The Troxler density probe was not available for measurements in the fine material.*

on neutron measurements made at a given depth was the difference, measured horizontally, between the two curves. This difference is referred to as measurement error and is expressed in percent moisture by volume.

Measurement errors were determined for each inch of depth for each graph and were plotted on total error graphs as the horizontal deviation from a vertical axis (figs. 7 through 10). The area under the error curve is the summation of the products of each measurement error and the inch of depth which each represents. Total error can be thought of as the total error in measurement (in inches of water) if neutron measurements had been made at each inch through the zone of influence around each void. The purpose of the computation of total error is to quantify the relative difference in the effect of a void as the water level changes.

Small Void--Coarse Sand

Figure 7A shows the results of measurements from the two tanks when the water levels were near the tops of the tanks; i.e., the area around the small void is saturated completely. The error in measurement at 24 inches below the surface was +17.5 percent by volume calculated by subtracting 45.0 percent for the control tank from 62.5 percent for the sample tank. From the surface of the sand down to a depth of 13 inches there is no measurement error due to the void. If readings were to be taken at each inch from 13 inches to 33 inches, the total error would be +1.86 inches.

Figure 7B shows the two curves when the water level had dropped to 18.75 inches below the surface. The void was still saturated and

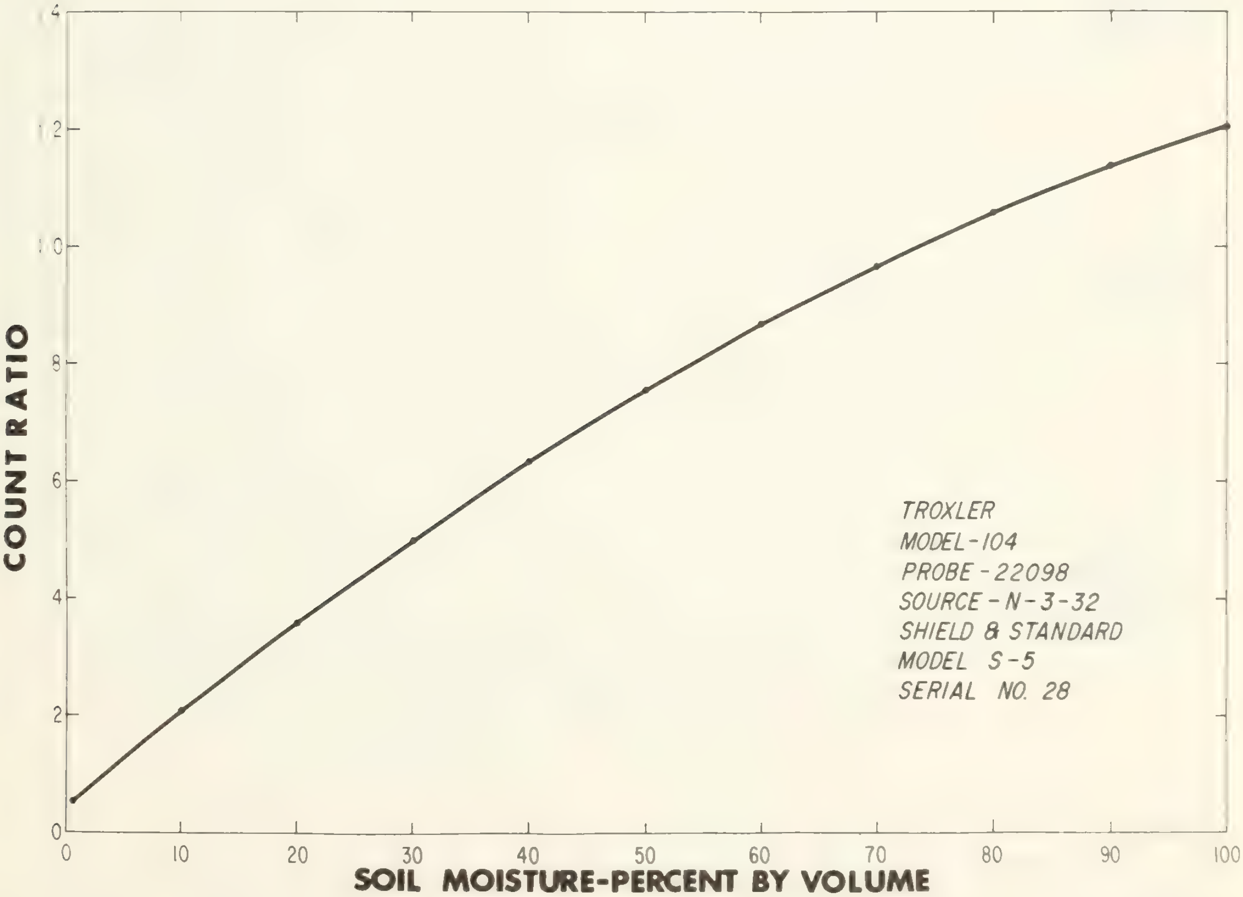

Figure 6. – Troxler calibration curve for a model 104 probe.

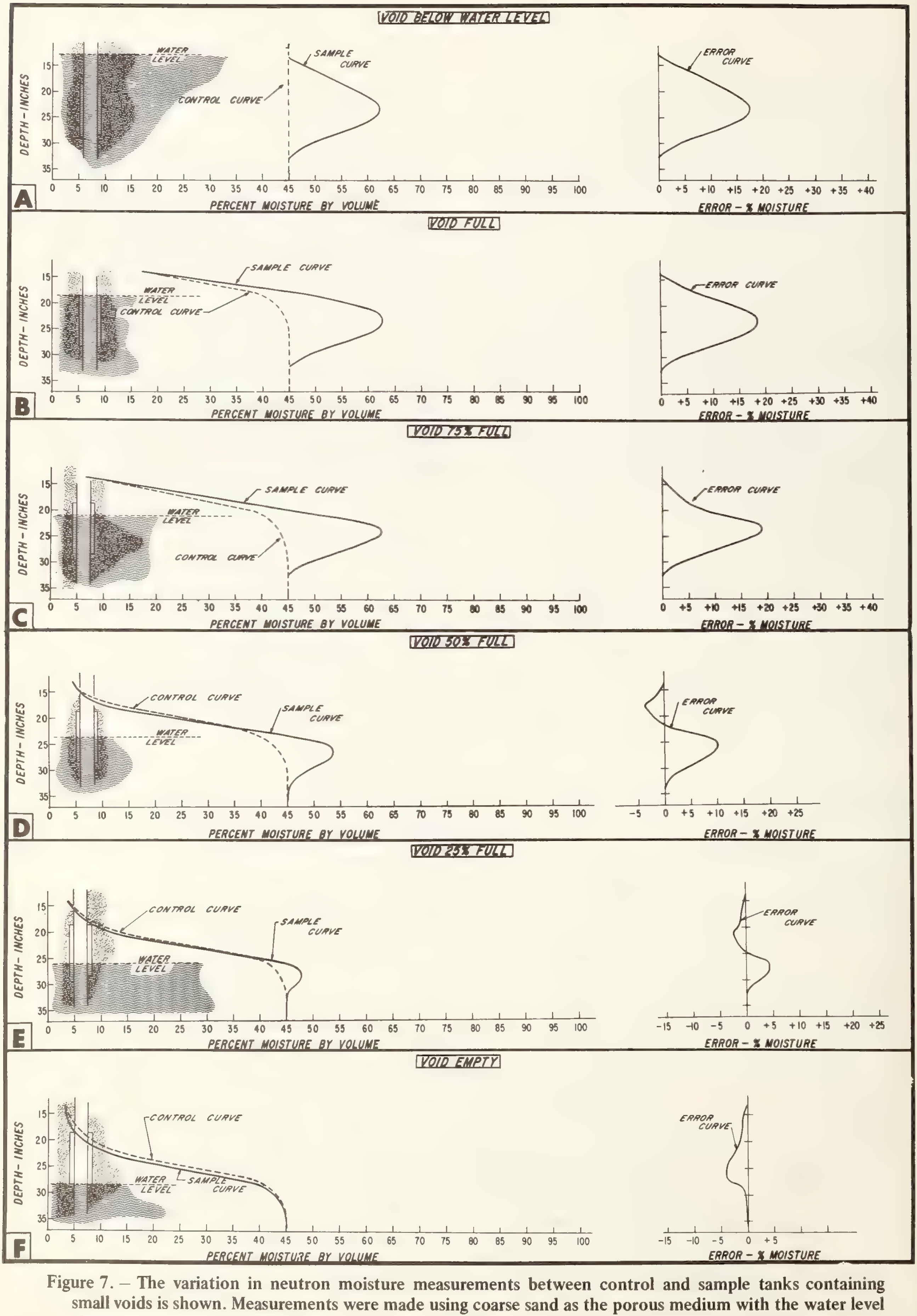

Figure 7. – The variation in neutron moisture measurements between control and sample tanks containing small voids is shown. Measurements were made using coarse sand as the porous medium with the water level changing with respect to the void.

the water level was at the top of the void. As the neutron source neared the water level, the moisture content increased linearly until the center of measurement reached the water level; then the true soil moisture content approached the saturated value of 45 percent (maximum pore volume) asymptotically. Thus, the neutron meter indicated that the water level (total saturation) was at 26 inches depth when the water level was actually at 18-3/4 inches depth. By comparing the control curve and the sample curve, it can be seen that there was no error when the probe was at 14 inches, but the positive error increased with depth as the fully saturated void strongly influenced the neutron measurement in the sample tank. The maximum positive error was +18.5 percent, or slightly higher than when the water level was at the surface of the medium. The reason for this was that the peak reading in the sample tank had not changed while the curve for the control tank flexed sharply under the effect of the lowered water table.

In figure 7C, the water level was down to 21-1/4 inches, and the void was three-fourths full. At 14 inches depth, there was no measurement error; at 23-3/4 inches depth, the measurement was +19.2 percent. The increase in positive error, when the void was not fully saturated, was caused by the lowering of the rounded portion of the control curve to a point opposite the peak in the sample curve. The total measurement error was +1.38 inches.

Figure 7D shows the situation when the water level was 23-3/4 inches below the surface and the void was half full. With the center of measurement at 14 inches depth, the source was on a level with the upper half of the void which acted as a large air gap and gave a negative measurement error. The water level just below the source acted to reduce the magnitude of the negative error. The total measurement error from 14 inches to 33 inches was +0.50 inch of water and was the algebraic sum of the negative and positive measurement errors.

Figures 7E and 7F show the reduction in the amount of positive measurement error as the water level dropped. When the void was entirely empty, the largest measurement error was -4.1 percent. The total measurement error was -0.35 inch.

Large Void--Coarse Sand

The measurement error caused by the large void was very similar in shape to that of the small void except that the magnitude of the errors was quite different. Figure 8A shows the water level above the large void, which means the medium surrounding the large void was saturated completely. The maximum measurement error was +55.0 percent moisture by volume, and the total measurement error through the void was +5.64 inches. In figure 8B the water level was 42 inches below the surface and at the top of the large void; the soil moisture curve for the control tank showed the same sharply reflexed shape as seen in figure 7B for the small void. The maximum measurement error was +55.0 percent and the total error was +5.52 inches. Figures 8C through 8F show the progressive reduction of the positive error and the increase of the negative error as the water-filled void became an air gap.

Small Void--Fine Sand

Figure 9A shows the results of measurements from the two tanks when the small void was fully saturated. The error in measurement with the probe at 24 inches below the surface was +16.5 percent by volume. The total measurement error from 13 inches to 33 inches below the surface was +1.54 inches of water.

Figure 9B shows the two curves with the water level dropped to 18-3/4 inches below the surface; the water level was at the top of the void. The maximum measurement error was +16.6 percent by volume with a total measurement error of +1.42 inches of water from 16 inches below the surface to 33 inches below the surface.

Figure 9D shows the two curves with the small void half full of water, a condition which produced only a small amount of negative measurement error. The maximum negative error was -3.1 percent moisture by volume, and the maximum positive error was +8.4 percent by volume. The total measurement error for the void was +0.32 inch of water.

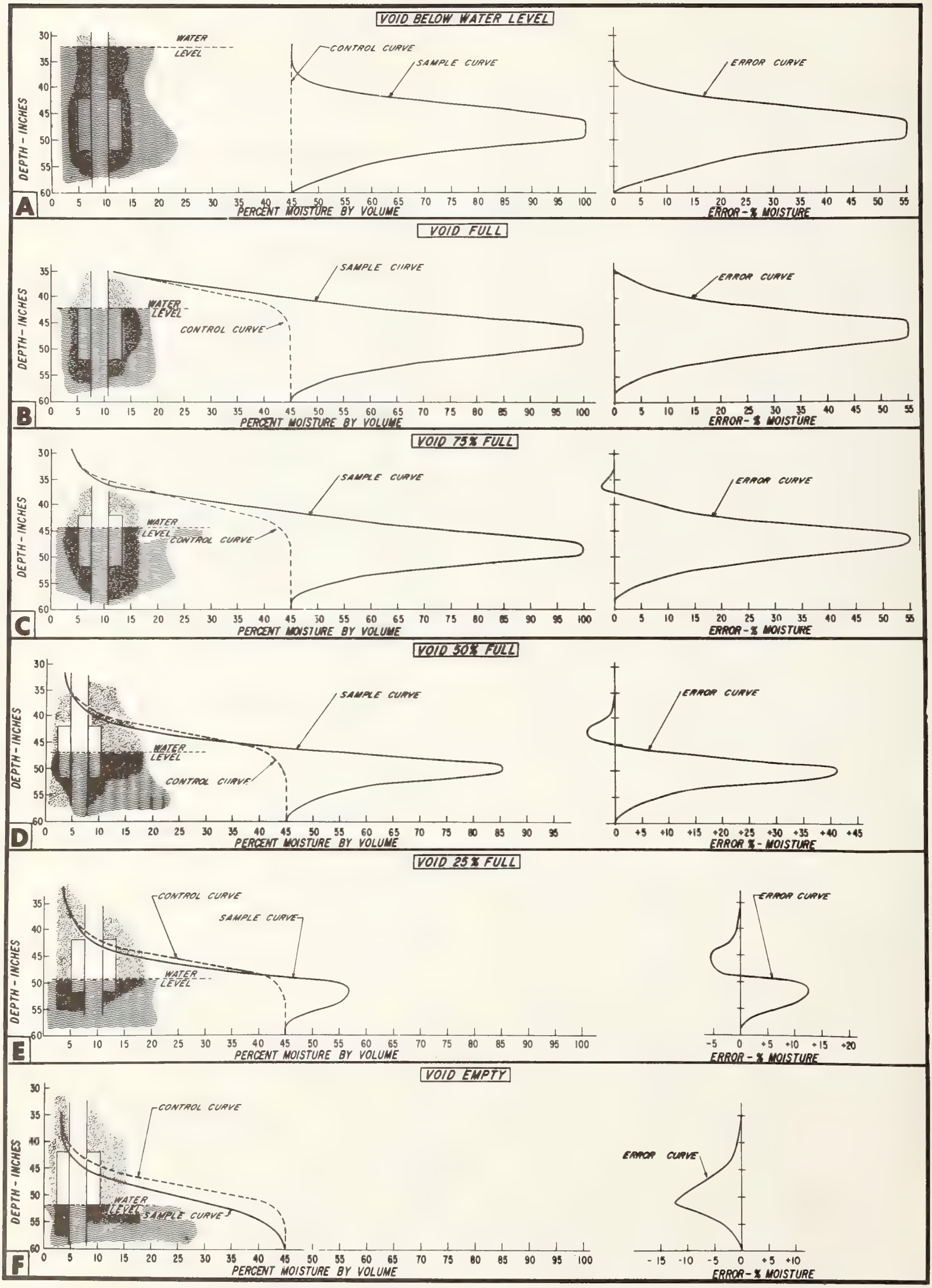

Figure 8. – The variation in neutron moisture measurements between control and sample tanks containing large voids is shown. Measurements were made using coarse sand as the porous medium when the water level was changing with respect to the void.

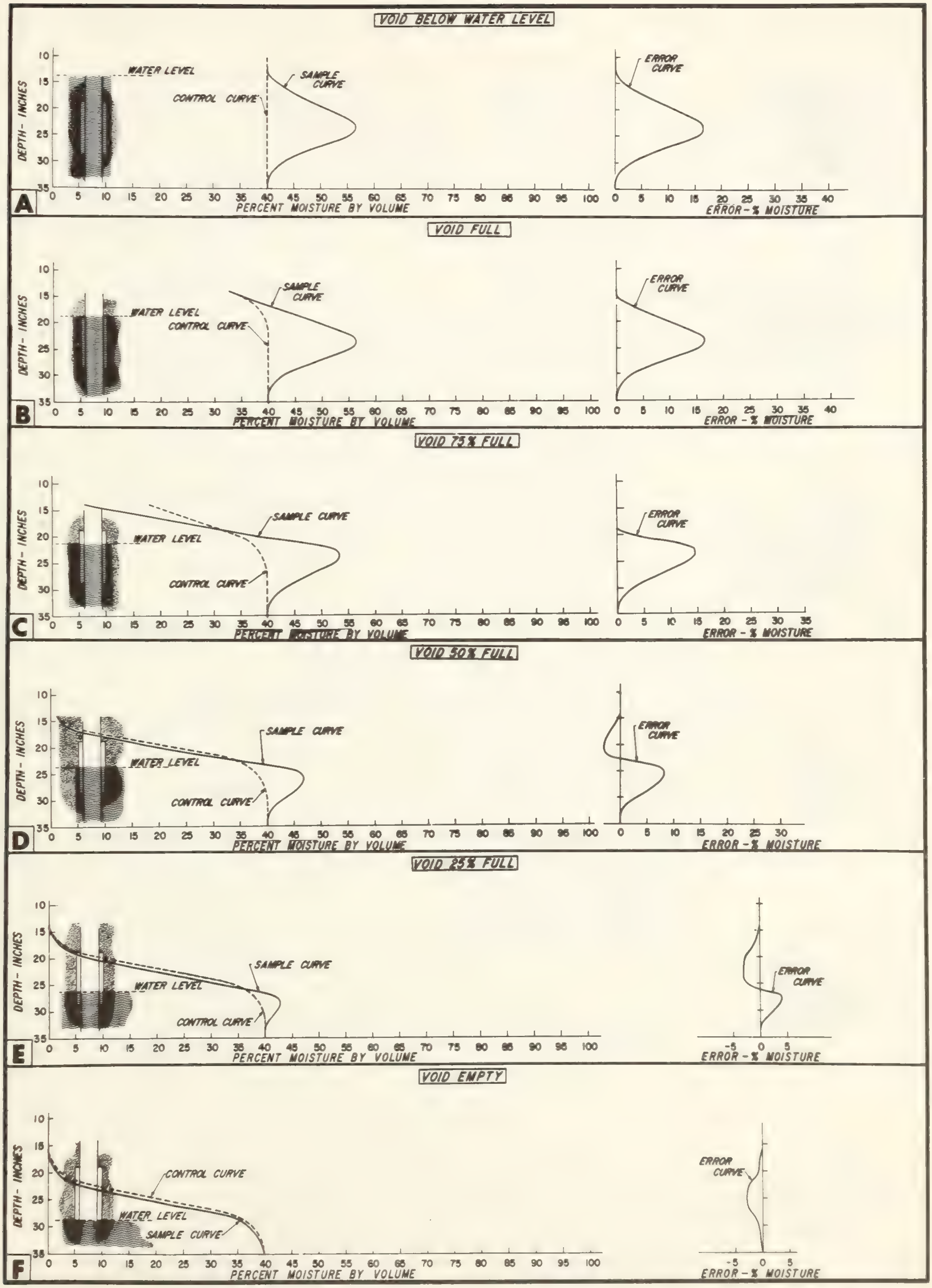

Figure 9. – The variation in neutron moisture measurements between control and sample tanks containing small voids is shown. Measurements were made using fine sand as the porous medium when the water level was changing with respect to the void.

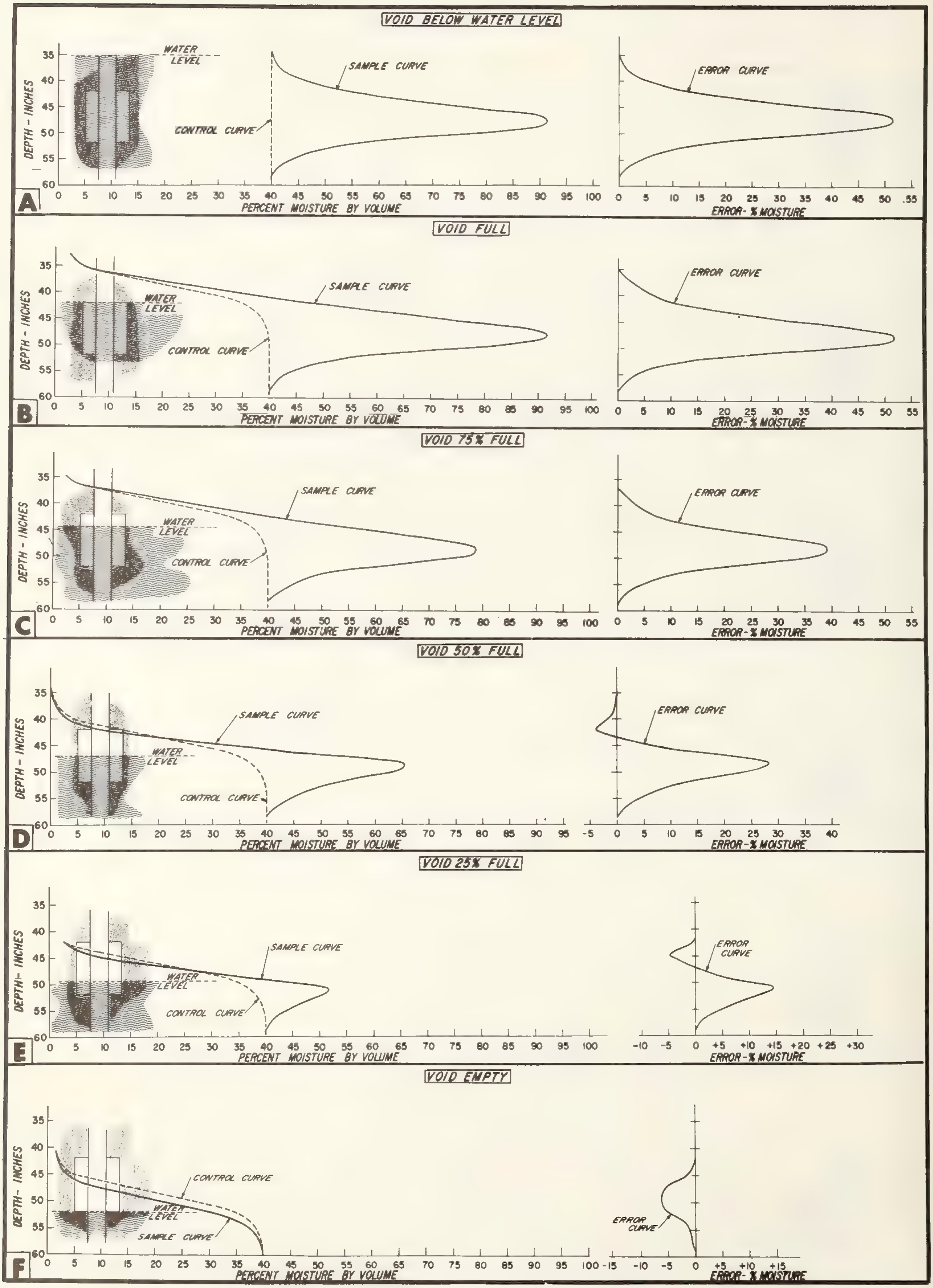

Figure 10. – The variation in neutron moisture measurements between control and sample tanks containing large voids is shown. Measurements were made using fine sand as the porous medium when the water level was changing with respect to the void.

Figures 9E and 9F show the continued increase in the amount of negative error as the water level is lowered within the small void. When the void was empty, the maximum measurement error was -3.0 percent by volume, and the total measurement error was -0.25 inch, from 16 inches below the surface to 35 inches below the surface.

Large Void--Fine Sand

Figures 10A through 10F show the same pattern of measurement-error change as the water level dropped within the large void. The maximum positive error was +52.2 percent moisture by volume with a maximum positive total error for the large void of +4.27 inches of water when the void was fully saturated. When the void was empty, the maximum negative error was -6.3 percent moisture by volume, and a maximum negative total error for the void of -0.50 inch of water.

It is interesting to note that when the measured medium contained less than 1 percent moisture, both curves are coincident and the voids caused no error (fig. 11).

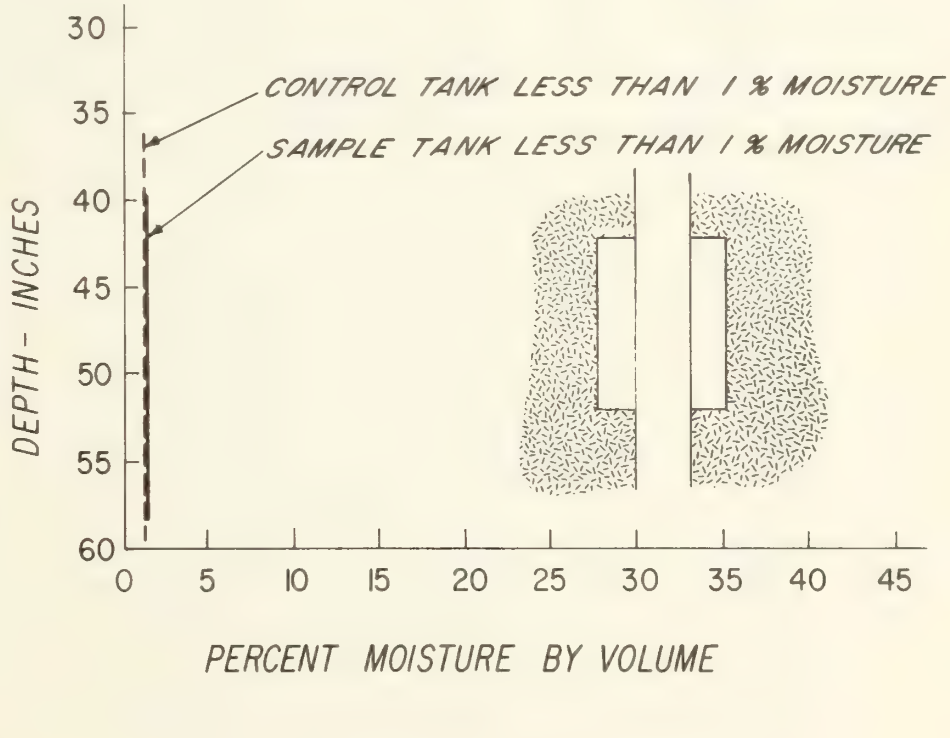

Figure 11. – When the measured medium contained less than 1 percent moisture, both moisture curves are coincident and the void causes no error.

DISCUSSION

Several conclusions can be drawn from figures 7 through 10. First, the presence of a void surrounding an access tube is most easily detected when the porous medium is saturated; this condition gives an error of the largest magnitude as shown in figures 7A, 8A, 9A, 10A, and table 2. The magnitude of the error at any level, and the magnitude of the total error, decrease as the water level falls with respect to the void. If the void is empty and the porous medium drained, the magnitude of the negative error is significantly less than the magnitude of the positive error.

The effect of the two densities of porous media is shown in figures 7A, 8A, 9A, 10A, and table 2. The material that has the highest bulk density gives the smallest value of positive measurement error and the lowest value of negative error. Figures 7A and 8A show that the total pore space of the coarse sand is 45 percent and figures 9A and 10A show that the total pore space of the fine sand is 40 percent. The increased amount of water in the coarse material caused a higher positive error. The smaller values of negative errors associated with the fine material were probably caused by reduced pore space.

Table 2. — Summary of maximum measurement errors and total errors for each void at each water level

Void size	Water level inches	Percent void saturation	Maximum measurement error %, moisture by volume[1]	Total error inches[2]
		COARSE SAND		
Small	Full	100	+17.5	+1.86
	18-3/4	100	+18.5	+1.79
	21-1/4	75	+19.2	+1.38
	23-3/4	50	-3.7 +10.3	+0.50
	26-1/4	25	-2.4 +4.5	+0.07
	28-3/4	0	-4.1	-0.35
Large	Full	100	+55.0	+5.64
	42	100	+55.0	+5.52
	44-1/2	75	-2.2 +55.0	+4.66
	47	50	-5.2 +41.3	+2.19
	49-1/2	25	-5.3 +12.6	+0.40
	52	0	-12.3	-0.99
		FINE SAND		
Small	Full	100	+16.5	+1.54
	18-3/4	100	+16.6	+1.42
	21-1/4	75	+14.8	+1.04
	23-3/4	50	-3.1 +8.4	-0.32
	26-1/4	25	-3.1 +4.2	-0.06
	28-3/4	0	-3.0	-0.25
Large	Full	100	+51.6	+4.17
	42	100	+52.2	+4.27
	44-1/2	75	+39.3	+3.19
	47	50	-3.9 +28.5	+1.67
	49-1/2	25	-4.8 +14.5	+0.56
	52	0	-6.3	+0.50

[1] *From error curve data — largest individual value.*

[2] *From error curve data — area under the curve with error expressed in inches of water instead of percent of volume.*

APPLICATION

The following example shows how the results of this laboratory study apply to field studies. Assume that soil moisture measurements are made at a certain depth within an access tube when the soil is saturated. If these measurements show a value of soil moisture which is greater than the maximum pore space of the soil, then a void adjacent to the tube should be suspected. Figure 12 illustrates such a hypothetical situation. The assumed maximum pore volume is 44 percent and the soil is assumed to be a coarse sand similar to that used in this study. This figure indicates that the soil moisture measurements, taken from late March to late June, are inaccurate because the measured soil moisture exceeds the maximum pore volume of the soil. If measurements are made at different depths in this tube during the time when the soil is saturated (in May for this example), the depth of the suspected void can be determined. Further measurements at 1-inch intervals may define a soil moisture curve similar to the solid line in figure 9A. A hypothetical field curve is shown as a solid line in figure 13 and illustrates the type of curve that might be encountered if there was a void partly filled with water. This field curve, which corresponds to the "control," is, of course, unknown; but a control curve may be drawn in after a study of the shape of the control curves in figures 7 through 10. An assumed control curve is shown as the dashed line in figure 13. The error curve is derived in the usual way from the horizontal displacement between the two curves and is shown at the right of figure 13; the total measurement error is the area ABCA. The 44 percent moisture ordinate is extended vertically until it intersects the hypothetical field curve at point D. Then a line is drawn horizontally from D to point E on the error curve. If the error curve is redrawn as the horizontal displacement between the control curve, the field curve, and the 44 percent ordinate, then this defines the error curve AEFA. Thus, soil moisture measurements may be made from a depth of 12 inches to a depth of 33 inches including a maximum estimated error of about +8.5 percent (at point E) instead of a maximum error of about 16 percent (at point B). The region of questionable data is shortened from the 12-inch level to about the 25-inch level instead of from the 12-inch level to the 33-inch level. The maximum measurement error is correspondingly reduced from +16 to +8.5 percent and the total error is reduced from 0.96 to 0.22 inch.

Figure 14 was derived from a plot of the maximum positive and maximum negative errors for both fine and coarse sand — a total of eight points taken from table 2. This graph can be used to estimate the volume of a suspected void provided that a field curve of neutron measurements can be made while the soil and void are saturated and provided that the saturated pore volume of the soil can be determined. In order to use figure 14, it is necessary to determine the maximum measurement error from field data. The field data are plotted, the saturated pore volume ordinate is superimposed, as in the left hand portion of figure 13, and the maximum measurement error is taken from this graph. Assume, for example, that the maximum measurement error for a completely saturated void in a coarse sand was +36 percent moisture by volume. Then, figure 14 is entered at 36 percent and followed vertically to the error curve for the coarse material. Move horizontally from this intersection to the negative error curve for the coarse material; from this point, the estimated maximum negative error of -6.5 percent moisture by volume can be found on the abscissa. Also, by continuing left horizontally from the negative error curve to the ordinate, the estimated volume of 62.50 cubic inches for the void can be found. The estimated maximum negative error is of interest because this value may be difficult, if not impossible, to measure in the field when the void is empty. It should be kept in mind that figure 14 was derived from laboratory data obtained from symmetrical voids. It is not known whether figure 14 will provide accurate estimates of the volume of an asymmetric void.

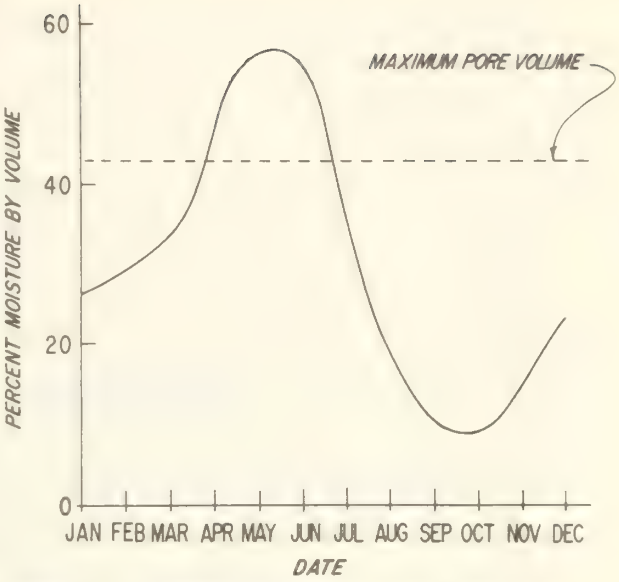

Figure 12. – Seasonal soil moisture for a given depth.

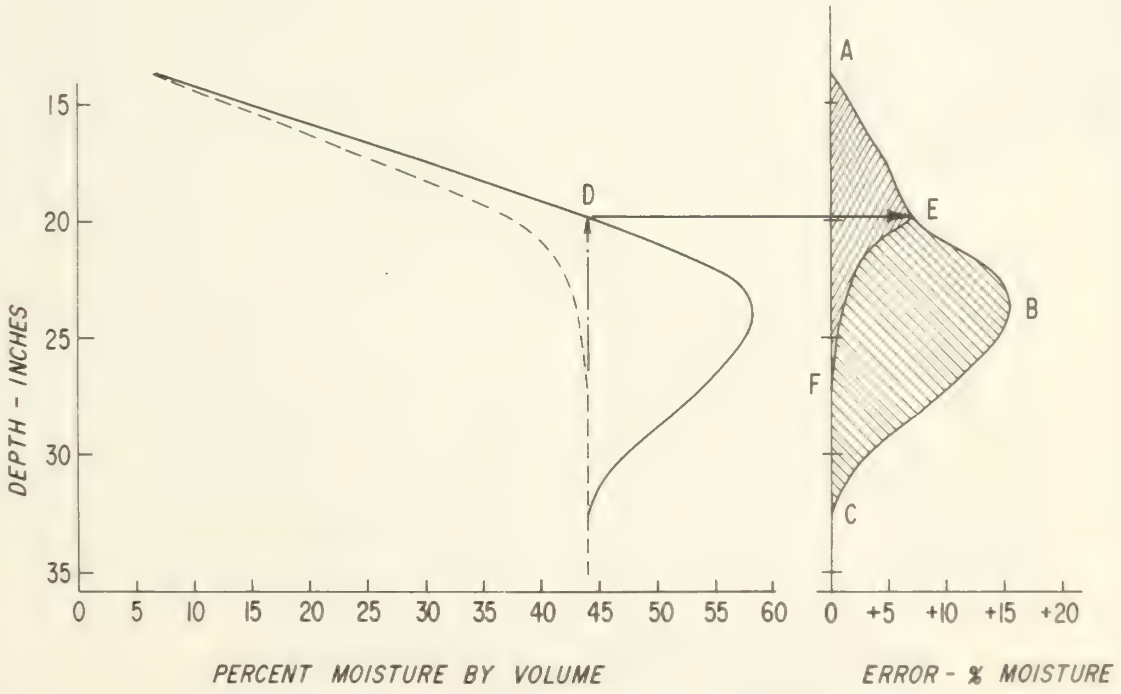

Figure 13. – Field data curve showing measurement error caused by a void partly filled with water.

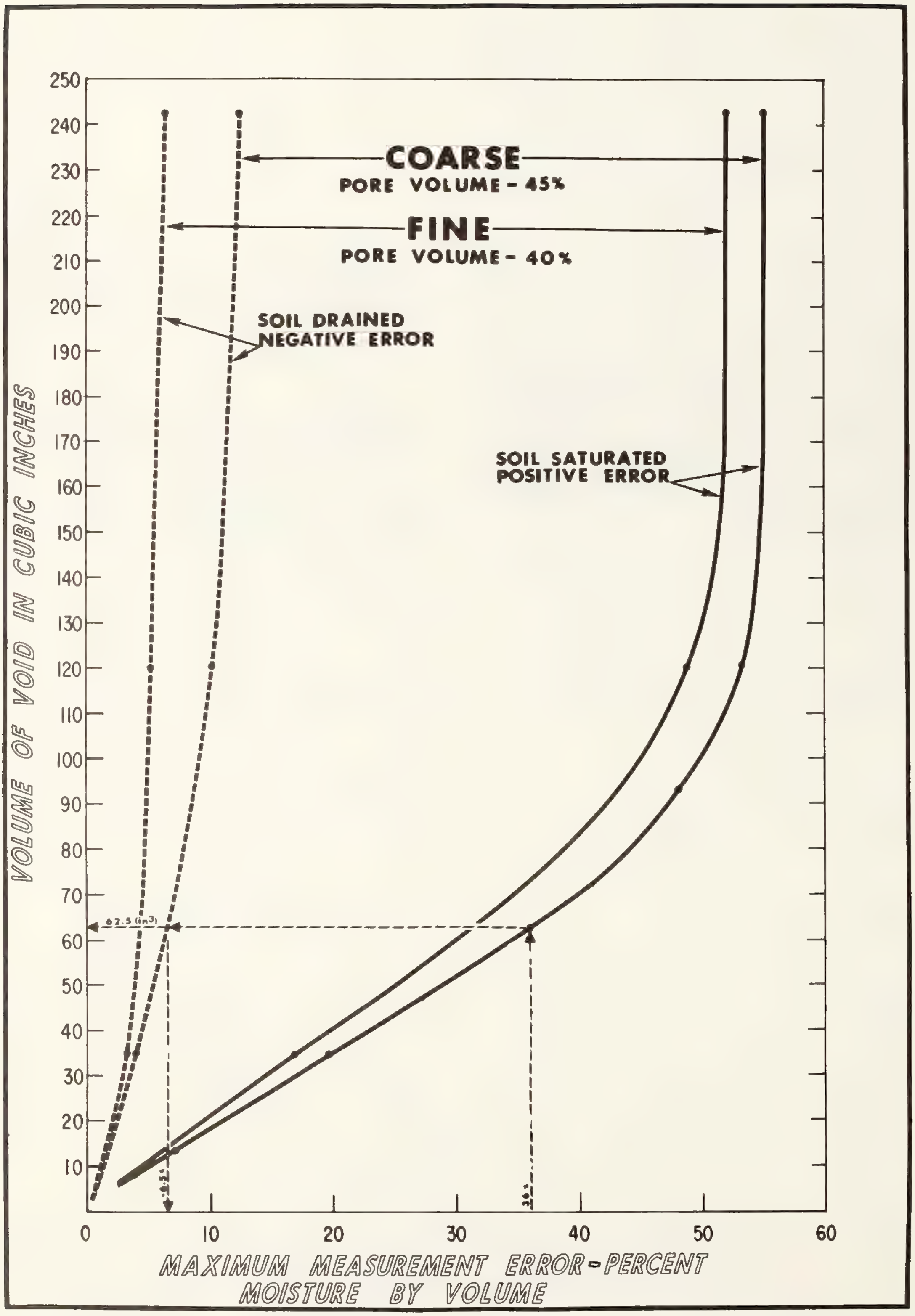

Figure 14. – Graph of volume of saturated void in cubic inches against the maximum measurement error in percent moisture by volume.

CONCLUSIONS

The figures and graphs of this paper are based on a laboratory study of the effect of air gaps and saturated voids on neutron moisture measurements. These results reflect the effect of symmetrical voids, each 10 inches long. Suggested procedures for estimating the amount and type of error (positive or negative) in field data may not yield accurate estimates for those voids which are greater than 3 inches in radius or shorter than 10 inches, or both. The Troxler equipment used in this laboratory study is nondirectional with respect to the axis of the void; therefore, the use of other neutron equipment which exhibits directional characteristics may yield significant differences when field studies are conducted on asymmetric voids.

The study described in this paper provides estimates of the maximum neutron measurement errors which may be expected for symmetric voids in a sand medium when the water is at different levels relative to the center of the void. Also, this study has shown that in the field the presence of a void can be determined most accurately when the soil is saturated. The magnitude of the positive measurement error will exceed that of the negative measurement error as long as any free water remains in the void.

Procedures which may be used to evaluate the magnitude of the measurement error from field data are outlined in this study. These procedures may be used to correct data for the effect of saturated voids surrounding the access tube, but they in no way reduce the importance of installing access tubes in such a way that there will be no voids next to the tube. Installation techniques together with descriptions of the equipment used have been reported elsewhere.

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Presents study results showing effects of voids on accuracy of neutron soil moisture measurements. A maximum error of +55 percent moisture by volume was caused by a large void in coarse sand with the void saturated; with the void drained, the error was -12.3 percent moisture. Errors in fine sand were slightly less than in coarse sand; errors in small voids were about one-third the magnitude of errors in large voids. Graphs were developed to estimate size of voids adjacent to access tubes and to calculate probable magnitude of measurement errors due to these voids.

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